CLAIMS

1. A rotary blood pump for use in a heart assist device or like device, said pump having an impeller suspended in use within a pump housing exclusively by hydrodynamic thrust forces generated by relative movement of said impeller with respect to and within said pump housing; and wherein at least one of said impeller or said housing includes at least a first deformed surface lying on at least part of a first face and a second deformed surface lying on at least part of a second face which, in use, move relative to respective facing surfaces on the other of said impeller or said housing thereby to form at least two relatively moving surface pairs which generate relative hydrodynamic thrust between said impeller and said housing which includes everywhere a localized thrust component substantially and everywhere normal to the plane of movement of said first deformed surface and said second deformed surface with respect to said facing surfaces; and wherein the combined effect of the localized normal forces generated on the surfaces of said impeller is to produce resistive forces against movement in three translational and two rotational degrees of freedom.
2. The blood pump of Claim 1 wherein said first deformed surface lies on at least part of a first face of said impeller.
3. The blood pump of Claim 1 wherein said second deformed surface lies on a second face of said impeller.
4. The blood pump of Claim 1 wherein said first deformed surface lies on a first inner face of said housing.

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5. The blood pump of Claim 1 wherein said second deformed surface lies on a second inner face of said housing.
6. The blood pump of Claim 1 wherein said first deformed surface covers entirely said first face.
7. The blood pump of Claim 1 wherein said first deformed surface covers entirely said second face.
8. The blood pump of any one of claims 1 to 7 wherein said first face lies at an acute angle relative to said second face.
9. The blood pump of claim 1 wherein said hydrodynamic forces are augmented by other forces to support said impeller for rotation within said housing.
10. The blood pump of claim 9 wherein said other forces include magnetic forces.
11. The blood pump of any one of Claims 1 to 10 wherein said first deformed surface comprises deformations in said first face of said impeller whereby a gap between said first deformed surface and a first facing surface on said housing forms, in use, a restriction in the form of a reducing distance between the surfaces with respect to the relative line of movement of said first deformed surface.
12. The blood pump of Claim 11 wherein said gap takes the form of a wedge shaped restriction which generates a thrust in use.
13. The blood pump of claim 1 wherein the pump is of centrifugal type or mixed flow type with impeller blades open on both front and back faces of said pump housing.
14. The blood pump of claim 1 wherein the front face of said pump housing is made conical, in order that the thrust perpendicular to a conical surface of said

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impeller has a radial component, which provides a radial restoring force to a radial displacement of the impeller axis during use.

15. The blood pump of claim 1 wherein the driving torque of said impeller derives from magnetic interaction between permanent magnets within blades of the impeller and oscillating currents in windings encapsulated in said pump housing.

16. The pump of claim 15 wherein said blades include magnetic material therein, the magnetic material encapsulated within a biocompatible shell or coating.

17. The pump of claim 16 wherein said biocompatible shell or coating comprises a diamond coating or other coating which can be applied at low temperature.

18. The pump of claim 16 wherein internal walls of said pump which can come into contact with said blades during use are coated with a hard material such as titanium nitride or diamond coating.

19. The pump of claim 1 wherein said impeller comprises an upper conical shroud having a taper or other deformed surface thereon and wherein blades of said impeller are supported below said shroud.

20. The pump of claim 19 wherein said impeller further includes a lower shroud mounted in opposed relationship to said upper conical shroud and wherein said blades are supported within said upper conical shroud and said lower shroud.

21. The pump of claim 1 wherein at least one of said deformed surfaces is located on said impeller.

22. The pump of claim 1 wherein at least one of said deformed surfaces are located on said housing.

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23. The pump of any one of Claims 1 to 22 wherein the combined effect of the localized normal forces generated on the surfaces of said impeller is to produce resistive forces against movement so as to support said impeller for rotational movement within said housing by said hydrodynamic thrust forces in an adaptive manner whereby said impeller is repositioned, in use, so as to conserve energy as a function of fluid viscosity.
24. The pump of any one of Claims 1 to 23 wherein the combined effect of said localized normal forces is to produce resistive forces against movement in three translational and two rotational degrees of freedom so as to support said impeller for rotational movement within said housing by said hydrodynamic thrust forces.
25. The pump of any one of claims 1 to 24 wherein forces imposed on said impeller in use are controlled by design so that, over a predetermined range of operating parameters, said hydrodynamic thrust forces provide sufficient thrust to maintain said impeller suspended in use within said pump housing.
26. The pump of any one of claims 1 to 25 incorporating control means which senses speed and input power from electrical parameters of electrical urging means which urge said impeller to rotate with respect to said pump housing thereby to estimate, in use, head pressure and/or flow rate of said pump.
27. The pump of Claim 25 further incorporating means to sense and prevent under pumping and regurgitation.
28. An estimation and control system for a pump; said pump of the type having an impeller located within a pump

cavity in a pump housing; said housing having a fluid inlet in fluid communication with said cavity; said housing having a fluid outlet in fluid communication with said pump cavity; said impeller urged to rotate about an impeller axis so as to cause fluid to be urged from said inlet through said pump cavity to said pump outlet; said impeller urged to rotate by impeller urging means; said impeller supported for rotational movement by impeller support means; said impeller maintained at or near a predetermined speed of rotation by control means acting on said impeller urging means; said control means receiving as input variables a first input variable comprising power consumed by said urging means; said control means receiving a second input variable comprising actual speed of rotation of said impeller; said control means thereby estimating head across the pump and/or rate of flow of said fluid to an approximation of predetermined accuracy relying on signals available from said urging means; said control system adapted to maintain speed of rotation of said impeller within a range whereby said impeller, in use, substantially resists five degrees of freedom of movement with respect to said pump housing predominantly without any external intervention from said control system to control the position of said impeller with respect to said housing.

29. The system of Claim 28 wherein said pump has a substantially constant steady state head versus flow rate characteristic over a predetermined flow rate range.

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30. The system of Claim 28 wherein blades of said impeller are such that a midline chord angle of said blades is inclined substantially radially to internal walls of said pump cavity.

31. The system of Claim 28 which relies on sensing of EMF induced in one or more coils forming part of said urging means.

32. The system of Claim 28 wherein said impeller includes blades inclined such that relative velocity of fluid off-flow from said blades is substantially radial with respect to said impeller axis.

33. The system of any one of Claims 28 to 32 wherein said impeller support means includes hydrodynamic support in up to five degrees of freedom.

34. The system of Claim 28 wherein said pump is a low specific speed pump.

35. The system of Claim 34 wherein said pump has a specific speed in the range 100-2000 rcv/min(gal/min)^{x}ft^{x}.

36. The system of Claim 34 wherein said pump has a specific speed of approximately 900-1000 rev/min(gal/min)^{x}ft^{-x}.

37. A rotary blood pump and an estimation and control system therefor, said pump having an impeller suspended hydrodynamically within a pump housing by thrust forces generated by the impeller during movement in use of the impeller as it rotates about an impeller axis; said estimation and control system as claimed in any one of claims 28 to 36.

38. The blood pump and estimation and control system of claim 37 wherein said thrust forces are generated by blades of said impeller.

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39. The blood pump and estimation and control system of claim 38 wherein said thrust forces are generated by forces of said blades of said impeller.
40. The blood pump and estimation and control system of claim 39 wherein said forces of said blades are tapered or non-planar, so that a thrust is created between the edges and the pump housing during relative movement therebetween.
41. The blood pump and estimation and control system of claim 38 wherein said forces of said blades are shaped such that the gap at the leading edge of the blade is greater than at the trailing edge and thus the fluid which is drawn through the gap experiences a wedge shaped restriction which generates a thrust.
42. The blood pump and estimation and control system of claim 37 wherein the pump is of centrifugal type or mixed flow type with blades of said impeller open on both front and back faces of the pump housing.
43. The blood pump and estimation and control system of claim 42 wherein the front face of the pump housing is made conical, in order that the thrust force perpendicular to the conical surface has a radial component, which provides a radial restoring force to a radial displacement of the impeller axis during use.
44. The blood pump and estimation and control system of claim 38 wherein the driving torque of said impeller derives from the magnetic interaction between permanent magnets within the blades of the impeller and oscillating currents in windings encapsulated in the pump housing.
45. The rotary blood pump and estimation and control system of claim 37 wherein said pump is of axial type.

46. The rotary blood pump and estimation and control system of claim 45 wherein within a uniform cylindrical section of the pump housing, said impeller includes tapered blade bearing surfaces which form a radial hydrodynamic bearing.
47. The rotary blood pump and estimation and control system of claim 46 wherein an interior of the pump housing is made with reducing radius at the two ends, and wherein the end hydrodynamic thrust forces have an axial component which can provide the axial bearing.
48. The rotary blood pump and estimation and control system of claim 46 wherein magnetic forces provide the axial bearing.
49. A rotary blood pump having a housing within which an impeller acts by rotation about an impeller axis to cause a pressure differential between an inlet side of the pump housing of said pump and an outlet side of the pump housing of said pump; said impeller suspended hydrodynamically by thrust forces generated by the impeller during movement in use of the impeller; said pump controlled by the estimation and control system of any one of claims 28 to 36.
50. The pump of claim 49 wherein said impeller includes magnetic material therein, the magnetic material encapsulated within a biocompatible shell or coating.
51. The pump of claim 50 wherein said biocompatible shell or coating comprises of a material which can be applied at low temperature.
52. The pump of claim 49 wherein internal walls of said pump which can come into contact with said blades during use are coated with a hard material such as titanium nitride.

53. A seal-less, shaft-less pump comprising a housing defining a chamber therein and having a liquid inlet to said chamber and a liquid outlet from said chamber; said pump further including an impeller located within said chamber; the arrangement between said impeller, said inlet, said outlet and the internal walls of said chamber being such that upon rotation of said impeller about an impeller axis relative to said housing, liquid is urged from said inlet through said chamber to said outlet; and wherein thrust forces are generated by relative movement of said impeller with respect to said housing ; said pump controlled by the estimation and control system of any one of claims 28 to 36.
54. The pump of claim 53 wherein said thrust forces are generated by blades of said impeller.
55. The pump of claim 54 wherein said thrust forces are generated by surfaces of said blades of said impeller.
56. The pump of claim 55 wherein said surfaces of said blades are tapered or non-planar.
57. The pump of claim 53 wherein said surfaces of said blades are shaped such that a gap at the leading edge of each of said blades is greater than at a trailing edge thereof whereby fluid which is drawn through the gap experiences a wedge shaped restriction which generates a thrust relative to said housing.
58. The pump of claim 54 wherein the pump is of centrifugal type or mixed flow type with said blades of said impeller open on both front and back faces of the pump housing.
59. The pump of claim 58 wherein the front face of the pump housing is made conical, in order that the thrust

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perpendicular to its conical surface at any point has a radial component, which provides a radial restoring force to a radial displacement of the impeller axis.

60. The pump of claim 58 wherein the driving torque of said impeller derives from the magnetic interaction between permanent magnets within the blades of the impeller and oscillating currents in windings encapsulated in the pump housing.

61. The pump of claim 53 wherein said pump is of axial type.

62. The pump of claim 61 wherein within a uniform cylindrical section of the pump housing, tapered blade surfaces form a radial hydrodynamic bearing.

63. The pump of claim 61 wherein the pump housing is made with reducing radius at opposed ends, and wherein the end hydrodynamic thrust forces have an axial component which can provide the axial bearing.

64. The pump of claim 61 wherein magnetic forces or other means can provide the axial bearing.

65. A pump having a housing within which an impeller acts by rotation about an axis to cause a pressure differential between an inlet side of a housing of said pump and an outlet side of the housing of said pump; said impeller suspended hydrodynamically in at least one of a radial or axial direction by thrust forces generated by the impeller during movement in use of the impeller; said pump controlled by the estimation and control system of any one of claims 28 to 36.

66. The pump of claim 65 wherein said impeller includes magnetic material therein, the magnetic material encapsulated within a biocompatible shell or coating.

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67. The pump of claim 66 wherein said biocompatible shell or coating comprises a diamond coating.
68. The pump of claim 66 wherein internal walls of said pump which can come into contact with said impeller during use are coated with a hard material such as titanium nitride.
69. The pump of claim 65 wherein at least upper and lower surfaces of blades of said impeller are interconnected by a structure having deformities in the outer surfaces thereof so that a thrust is created between said surfaces and the adjacent pump casing during relative movement therebetween.
70. A method of hydrodynamically suspending and controlling an impeller within a rotary pump for support in at least one of a radial or axial direction; said method comprising incorporating a deformed surface in at least part of said impeller so that, in use, a thrust is created between said deformed surface and the adjacent pump casing during relative movement therebetween; said method further including the step of maintaining speed of rotation of said impeller within a range whereby said impeller, in use, substantially resists five degrees of freedom of movement with respect to said pump housing without any external intervention.
71. The method of claim 70 wherein said deformed surface includes a taper.
72. The method of claim 71 wherein said taper is arranged so that there is a larger gap at a leading edge thereof between said impeller and said pump casing than at a trailing edge thereof.

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73. An estimation and control system for a pump; said pump of the type having an impeller located within a pump cavity in a pump housing; said housing having a fluid inlet in fluid communication with said cavity; said housing having a fluid outlet in fluid communication with said pump cavity; said impeller urged to rotate about an impeller axis so as to cause fluid to be urged from said inlet through said pump cavity to said pump outlet; said impeller urged to rotate by impeller urging means; said impeller supported for rotational movement by impeller support means; said pump maintained at or near a predetermined operating point by control means acting on said impeller urging means; said control means receiving as input variables at least a first input variable derived from said urging means; said control means receiving at least a second input variable also derived from said urging means; said control means thereby calculating an estimate of said operating point to an approximation of predetermined accuracy relying on signals available from said urging means; said control means controlling said pump by comparing said predetermined operating point with said estimate of said operating point; and wherein instantaneous pump speed and electrical input power are allowed to be modulated by the heart, in use, by appropriate selection of a control time constant.
74. The system of Claim 73 in combination with said pump.
75. The system of Claim 73 or Claim 74 wherein said control time constant of the control system is greater than the rotational, inertial time constant of the impeller.

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76. The system of Claim 73 or Claim 74 wherein said control time constant is at least one cardiac cycle.

77. The system of any one of Claims 73 to 76 wherein said first input variable comprises instantaneous pump speed.

78. The system of any one of Claims 73 to 77 wherein said second input variable is representative of electrical input power to said impeller urging means.

79. The system of any one of Claims 73 to 78 wherein said pump is arranged to operate according to a relatively flat HQ characteristic.

80. The system of any one of Claims 73 to 79 wherein variation in speed of said impeller, in use, is permitted and then utilised to calculate an improved estimate of pressure rise across the pump and flow through it.

81. The system of Claim 79 wherein said HQ characteristic is sufficiently flat that head will remain constant to a sufficient approximation over a predetermined operating range whereby, over said operating range, said system can assume that pump speed will be proportional to flow rate.

82. The system of any one of claims 63 to 81 wherein said predetermined operating point is calculated so as to maintain minimum pump speed such that the minimum head pressure across the pump does not increase.

83. The system of Claim 82 wherein said system ensures that minimum pump speed is always greater than or equal to the minimum speed at which non-regurgitant flow will occur.

84. The system of Claim 83 wherein the speed at which regurgitant or negative flow will begin to occur is

determined as that pump set point speed where levels and phase lags between pump outlet and inlet pressures fall during diastole cause flow reversal.

85. The system of Claim 84 wherein the pump speed at which regurgitation is calculated to occur is calculated according to:

Nregurg = N (t) for Qdiastole = 0L/min

86. A physiological controller for use in association with a pump; said controller monitoring estimated flow of fluid within said pump and pressure across said pump by non-contact means thereby to control speed of rotation of an impeller within said pump; and wherein said controller permits impeller speed to vary under a pulsating fluid load thereby to assist in calculation and adjustment of impeller speed set point.

87. The controller of Claim 86 wherein said fluid is blood; said controller incorporating calculation means which determines optimal pump output for said pump to meet demand for blood at all physiological states of a mammal in which said pump is installed.

88. The controller of Claim 87 wherein said control means includes as a control aim to adjust pump output so as to eliminate suction collapse of blood vessels.

89. The controller of Claim 88 wherein said control means calculates flow and head (peak and RMS values) to discern optimal pumping based on collapse and overpumping.

90. The controller of Claim 88 wherein said control means calculates values of speed and power (peak and RMS values) to discern optimal pumping based on collapse and overpumping.

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91. The controller of Claim 88 wherein said control means includes a control aim which adjusts optimal pump output to a point close to where the aortic valve just opens or just fails to open.
92. The controller of claim 91 wherein said pump comprises a ventricular assist device adapted to assist operation of a ventricle of a heart and wherein said control means adjusts pump output so that, in alternating fashion, said ventricle in conjunction with said aortic valve is allowed to eject blood over a predetermined number of cardiac cycles and then said ventricle in conjunction with said aortic valve is caused to not eject blood over a following predetermined number of cardiac cycles.
93. An estimation and control system for a pump; said pump of the type having an impeller located within a pump cavity in a pump housing; said housing having a fluid inlet in fluid communication with said cavity; said housing having a fluid outlet in fluid communication with said pump cavity; said impeller urged to rotate about an impeller axis so as to cause fluid to be urged from said inlet through said pump cavity to said pump outlet; said impeller urged to rotate by impeller urging means; said impeller supported for rotational movement by impeller support means; said pump maintained at or near a predetermined operating point by control means acting on said impeller urging means; said control means receiving as input variables at least a first input variable derived from said urging means; said control means receiving at least a second input variable also derived from said urging means; said control means thereby calculating an estimate of

said operating point to an approximation of predetermined accuracy relying on signals available from said urging means; said control means controlling said pump by comparing said predetermined operating point with said estimate of said operating point; and wherein said pump is arranged to operate according to a relatively flat HQ characteristic.

94. The estimation and control system of Claim 93 wherein there is no inflexion point in said HQ characteristic at or near said predetermined operating point.

95. The estimation and control system of Claim 93 or Claim 94 wherein said pump includes near-radial off-flow from said impeller.

96. The estimation and control system of Claim 93 or Claim 94 or Claim 95 wherein said pump has a low specific speed.